Title	Coulomb Effect in Nucleon–Deuteron Elastic Scattering
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Citation	Few-Body Systems (2013), Articles not assigned to an issue
Issue Date	2013-01
URL	http://hdl.handle.net/2433/170258
Right	The final publication is available at www.springerlink.com
Type	Journal Article
Textversion	author

Few-Body Systems (FB20) manuscript No.
(will be inserted by the editor)

Coulomb effect in Nucleon-Deuteron Elastic Scattering

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Received: date / Accepted: date

Abstract We have applied the quark-model nucleon-nucleon interaction fss2 to the nucleon-deuteron scattering. The screened cutoff Coulomb force in the momentum space has been incorporated to the proton-deuteron scattering by extending the matching condition, which is proposed by Vincent and Phatak for the sharply cutoff Coulomb problem. The model fss2 can reproduce the overall characteristics of the experimental data. It is found that fss2 partially incorporates the attractive feature, which accords with the good reproduction of the triton binding energy and neutron-deuteron doublet scattering length. This attractive feature is due to the off-shell effect related to the quark-model description of the short-range repulsion of the two-nucleon force.

Keywords Quark-model nucleon-nucleon interaction · Nucleon-deuteron scattering

1 Introduction

The three-nucleon ($3N$) system is appropriate to study the nucleon-nucleon (NN) interaction since many techniques for rigorous calculations have been developed. The quark-model (QM) baryon-baryon interaction is constructed in the framework of the resonating-group method for two three-quark clusters. The short-range repulsion of the NN interaction is mainly described by the nonlocal quark-exchange kernel, which gives quite different off-shell properties from standard meson-exchange potentials. The deficiency of the triton binding energy by our QM NN interaction fss2 [1] is about

Presented at the 20th International IUPAP Conference on Few-Body Problems in Physics, 20 - 25 August, 2012, Fukuoka, Japan

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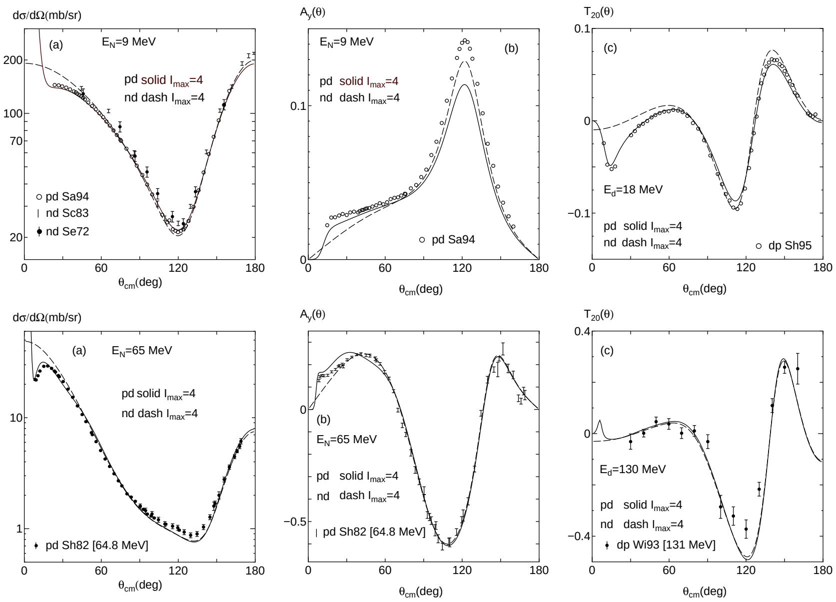

Fig. 1 Nd elastic scattering observables at $E_N = 9$ (upper panels) and 65 MeV (lower panels), compared with the experimental data; (a) the elastic differential cross section $d\sigma/d\Omega$, (b) the nucleon vector analyzing power $A_y(\theta)$, and (c) the deuteron tensor analyzing power $T_{20}(\theta)$. The solid curves show the results of the pd calculations using the Coulomb cutoff radius $\rho = 8$ fm, and the dashed curves show nd predictions. The experimental data. are taken from Refs. [2] for Sa94, [3] for Sc83, [4] for Se72, [5] for Sh95, [6] for Sh82 and [7] for Wi93.

350 keV [8], which is far smaller than 0.5 – 1 MeV, predicted by standard meson-exchange potentials. It is therefore interesting to examine the nonlocal effect of QM NN interaction on the $3N$ scattering observables.

The Coulomb force should be taken into account for the comparison with ample and precise experimental proton-deuteron (pd) scattering data. The incorporation of the Coulomb force to the three-body scattering problem is a challenging task. In recent years, some development have been made based on the Kohn variational approach [9] and on the coodinate space Faddeev integral equations [10,11]. The standard treatment in the momentum space is the screening and renormalization approach [12–14]. In this contribution, a newly-developed method in Ref. [15] based on the Vincent-Phatak method [16] is successfully applied to the pd elastic scattering and we examine the off-shell effect of the QM NN interaction.

2 Results

In applying fss2 to the nucleon-deuteron (Nd) elastic scattering in the Faddeev formalism for composite particles, the Alt-Grassberger-Sandhas equations [17] are solved in the momentum space. The channel-spin formalism is used. We introduce the NN interaction up to the total angular momentum $I_{\max} = 4$. The charge independence

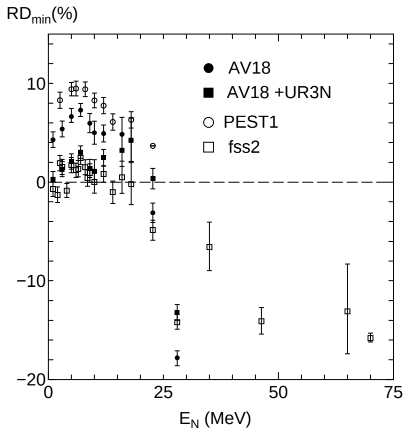

Fig. 2 Relative deviation of the *pd* differential cross section minima from the experimental data. The experimental data are taken from [2]. The AV18 (filled circles) and AV18+URIX $3N$ results (filled squares) are from Kievsky *et al.* [9] and the results using the PEST1 potential (open circles) are from Alt *et al* [12].

breaking and charge symmetry breaking are not included, nor the $3N$ isospin $T = 3/2$ component for the *pd* scattering. Our calculations do not introduce $3N$ forces.

The sharply cutoff Coulomb force is introduced at the quark level, which leads to the error-function-type Coulomb force between two protons. The screened Coulomb force between the proton and the deuteron is obtained by folding the *pp* Coulomb potential with the realistic deuteron wave function. We calculate the NN t-matrix for isospin 1 channel using $t^{I=1}_{\text{eff}} = (2/3)t_{pp} + (1/3)t_{np}$ [18]. In Ref. [15], we propose a practical method of solving the screened Coulomb problem by extending the Vincent-Phatak method for the sharply cutoff Coulomb force [16]. We can extract the nuclear phase shift by imposing the matching condition for the asymptotic wave functions.

We have examined the Nd elastic scattering observables up to $E_N = 65$ MeV. Some examples are shown in Fig. 1. The overall characteristic of the experimental data is reproduced, while discrepancies at the maximum points of the vector analyzing power (so-called “A_y puzzle”) still exist. The Coulomb effect is important at all angles in the low-energy region, but confined to forward angles in the higher energy region.

The energy dependence of the minimum points of the elastic differential cross sections (diffraction minima) is often discussed as Sagara discrepancy [2] and is very important to discuss the $3N$ force effect. In order to examine the energy dependence of the diffraction minima quantitatively, we show in Fig. 2 the relative differences, which are defined by $\text{RD}_{\min} = [\left(\frac{d\sigma}{d\Omega}\right)_{\text{cal.}}(\theta_{\min}) - \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}}(\theta_{\min})]/\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}}(\theta_{\min})$ in the energy region $E_p < 70$ MeV. On the low-energy side $E_p < 18$ MeV, the minimum values of the *pd* differential cross sections calculated by fss2 reproduce the experimental data at accuracy less than 2%. In Ref. [9], the Urbana IX (URIX) $3N$ potential lessens the cross sections at the diffraction minima, resulting in a good agreement with the experimental data. In our result, fss2 takes into account this attractive effect at the NN level. This result accords with the good reproduction of the triton binding energy and *nd* doublet scattering length [19].

3 Summary

We have incorporated the screened Coulomb potential for the *pd* scattering and examined elastic scattering observables up to $E_N = 65$ MeV. The QM NN interaction fss2 can reproduce the overall characteristics of the experimental data. We have found, from the analysis of the diffraction minima, that fss2 partially incorporates the attractive effect in the doublet S-channel, which is usually attributed to the $3N$ force in the standard description by meson-exchange potentials. These results reflect the off-shell effect related to the non-locality of the QM NN interaction.

Acknowledgements This work was supported by Grants-in-Aid for Scientific Research (S) and (C) from the Japan Society for the Promotion of Science (JSPS) (Grant No. 23224006 and No. 23540302, respectively), and by a Grant-in-Aid for the Global COE Program "The Next Generation of Physics, Spun from Universality and Emergence" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. It was also supported by core-stage backup subsidies from Kyoto University. The numerical calculations were carried out on SR16000 at YITP in Kyoto University and on the high-performance computing system Intel Xeon X5680 at RCNP in Osaka University.

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